Oscillatory dependence of the threshold field for the disruption of a charge density wave in $NbSe_3$ on the amplitude of the rf pump field

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An oscillatory dependence of the threshold field for the disruption of a charge density wave on the amplitude of the rf field has been observed in $NbSe_3$ samples of small cross-sectional area subjected to an external rf pump. This oscillatory dependence is predicted by the classical and tunneling models for the motion of a charge density wave in a periodic impurity potential.

When an rf pump field is applied to a quasione-dimensional sample under conditions corresponding to the motion of a charge density wave, steps of constant current of the charge density wave (Shapiro steps) appear on the I-V curve. These steps correspond to the condition that the frequency of the internal current oscillations of the charge density wave, ω_i, is a multiple of the frequency of the pump field, ω: $p\omega_i = q\omega$ (p and q are integers).[1,2] In general, the experimental behavior of the height of the steps as a function of the amplitude (E_{rf}) and the frequency of the pump field[2] agrees with the classical[3] and tunneling[4] models for the motion of a charge density wave. One of the most important discrepancies with Refs. 3 and 4 was the absence in the experiments of Refs. 2, 4, and 5 of the oscillations predicted in Refs. 3 and 4 in the plot of the threshold field for the disruption of a charge density wave, E_T, versus E_{rf}. This discrepancy has cast doubt on the validity or at least the applicability of these models in the region $E \sim E_T$.

In the present letter we report the first results of an observation and study of oscillations in the $E_T(E_{rf})$ dependence.[1)]

In contrast with the earlier studies, we used for our measurements $NbSe_3$ samples of small cross-sectional area, 2×10^{-10}–5×10^{-9} cm^2, which is known[8] to lead to a high coherence in the motion of the charge density wave.

Figure 1 shows a series of curves of the differential conductivity σ_d versus the bias voltage across the sample, V, for various amplitudes of the pump field, V_{rf}, at the frequency 0.8 GHz. At $V_{rf} = 0$, the pinning state is left abruptly as V is increased, at $V = V_T$. At the time of the disruption of the charge density wave, σ_d goes through a sharp maximum and then decreases to a constant value σ_d^{ac}. This asymptotic behavior $\sigma_d(V)$ is characteristic of the model of the motion of a rigid charge density wave.[3] It also follows from a model which incorporates a deformation of the charge density wave in the limit in which the size of the domain of the charge density wave is larger than the size of the sample.[9] The jump in σ_d at $V = V_T$ is explained on the basis that at $V = V_T$ the charge density wave begins to move immediately, as a whole, along the entire volume of the sample. As V_{rf} increases (to $V_{rf} \approx 220$ mV), V_T is observed to

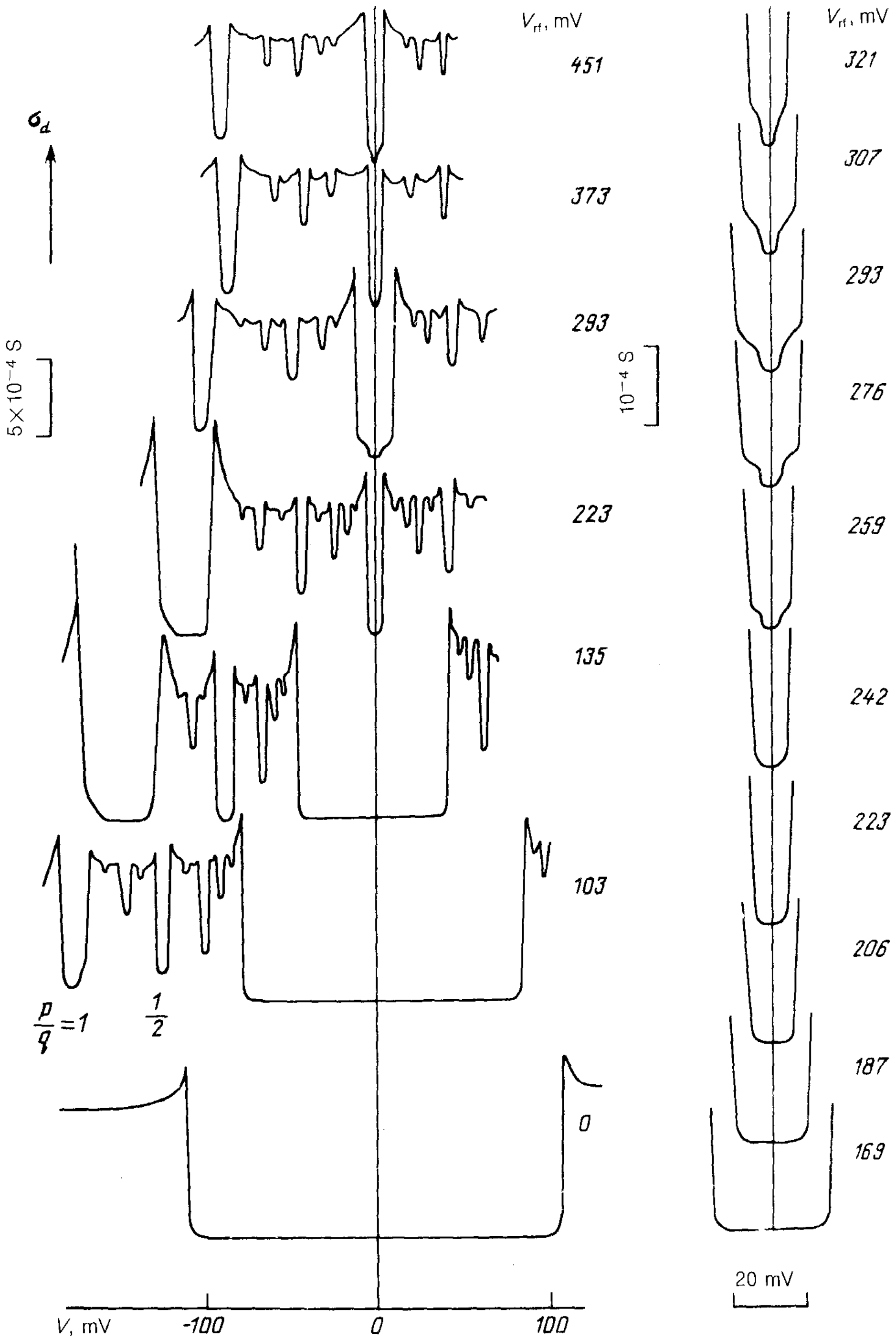

FIG. 1. Series of curves of $\sigma_d(V)$ for a $NbSe_3$ sample with dimensions of $(2.5\times10^{-9}\ cm^2)$ (0.05 cm) for various peak values of the rf field, V_{rf} ($T = 39$ K). The origins for the curves for $V_{rf} > 0$ have been displaced upward. The initial parts of the $\sigma_d(V)$ curves are shown in more detail at the right.

decrease; in addition, Shapiro steps appear and develop. Beginning at $V_{rf} \approx 120$ mV, the value of σ_d at the first step ($p/q = 1$) reaches the value of σ_d in the pinning state of the charge density wave (the condition for complete synchronization of the oscillations with $p/q = 1$ during the motion of the charge density wave). In addition, a complete synchronization of oscillations with $p/q = 1/2$ is observed. The behavior of σ_d at $V \sim V_T$ and the complete synchronization of the current oscillations of the charge density wave are evidence that the motion of the charge density wave is highly coherent, approximately a single-domain motion in the samples studied.[9,10]

With a further increase in V_{rf}, at $V_{rf} \gtrsim 220$ mV, the oscillations appear in the $V_T(V_{rf})$ dependence: V_T initially increases (Fig. 1; the curve for $V_{rf} = 293$ mV), then decreases (373 mV), and then increases again (451 mV). Figure 2 shows the oscillatory dependece $V_T(V_{rf})$ found. At $V_{rf} \gtrsim 220$ mV, at which the first oscillation in the $V_T(V_{rf})$ dependence begins, we see the appearance of a fine structure in $\sigma_d(V)$ (the right side of Fig. 1; the curves for $V_{rf} = 259$–321 mV). This fine structure is manifested as an increase of σ_d by 2–7% in fields lower than V_T by a factor of 1.5–3.

For the lower-quality samples, in which the motion of the charge density wave apparently did not reach a single-domain nature [the absence of the condition for complete synchronization; the presence of a characteristic dip in $\sigma_d(V)$ at $V \gtrsim V_T$, below the value of σ_d^{ac}; Ref. 9], the oscillations in $V_T(V_{rf})$ are essentially washed out.

An oscillatory dependence $V_T(V_{rf})$ follows from the theory describing the motion of a charge density wave in a periodic impurity potential.[3,4] In the classical model of Ref. 3, for example, the motion of the charge density wave is described by

$$m\ddot{x} + 1/\tau\,\dot{x} + \frac{m\Omega_c}{Q\tau}\sin Qx = e(E + E_{rf}\sin\omega t), \tag{1}$$

where m and Q are respectively the mass and wave vector of the charge density, and the characteristic frequency is $\Omega_c = \omega_o^2\tau$, where ω_0 is the natural frequency of the oscillations of the charge density wave, and $1/\tau$ describes the friction of the wave. The tunneling model deals with a nonsinusoidal periodic potential for the interaction of the charge density wave with impurities.[4] Figure 2 compares the experimental dependence $V_T(V_{rf})$ with the dependence predicted by Eq. (1) for $\omega/\Omega_c = 1.3$. Although the magnitude of the oscillations is less than the theoretical prediction, and the oscillations do not "dip" to zero (see the inset in Fig. 2), the qualitative nature of the experimental dependence and the oscillation period agree well with (1). The value of Ω_c which fits the experimental $V_T(V_{rf})$ best according to the κ criterion[11] is 610 MHz. This figure is close to data on the frequency dependence of the maximum amplitude of the first Shapiro step[12] measured for the same sample: $\Omega_c = 560$ MHz.

The value of Ω_c found previously[2] for $NbSe_3$ samples with threshold fields that were lower (by a factor of about 7) was ~ 100 MHz, so that the ratio Ω_c/E_T is roughly the same for our samples and for the $NbSe_3$ samples in Ref. 2. In the model of Ref. 3, the corresponding quantity is $\Omega_c/E_T = Qe\tau/m$. The fact that the value of Ω_c/E_T is the same for different samples apparently means that τ depends only weakly on the impurity concentration in $NbSe_3$, as in TaS_3 (Ref. 13).

To reach a qualitative understanding of the physical meaning of the oscillatory

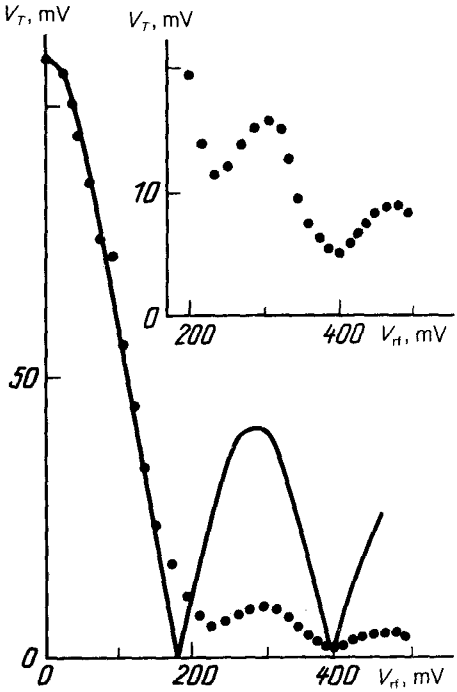

FIG. 2. The dependence $V_T(V_{rf})$ found experimentally and that calculated from (1) with $\omega/\Omega_c = 1.3$ (solid line).

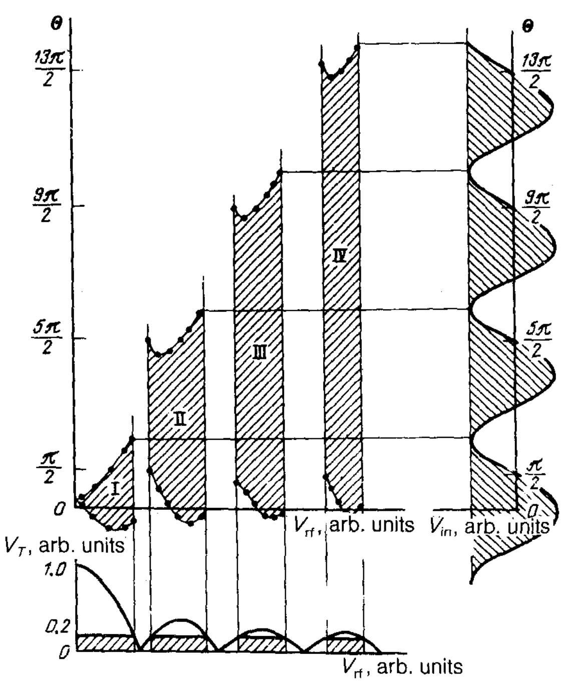

FIG. 3. Behavior of V_T and of the boundaries of the regions in which the phase (θ) of the charge density wave is localized as V_{rf} increases. The calculation based on (1) was carried out for a static field $V_0 = 0.2V_T$ and for the parameter values $\omega/\Omega_c = 1.2$ and $(\omega_0\tau)^2 = 0.2$. Shown at the right is the impurity potential $V_{in}(\theta)$.

$V_T(V_{rf})$ dependence, we worked from Eq. (1) to numerically analyze the behavior of the phase of the charge density wave, $\theta = Qx$, in a weak static field $V_0 = 0.2V_T$ as a function of V_{rf}. Figure 3 shows the behavior of the region in which $\theta(V_{rf})$ and $V_T(V_{rf})$ vary up to V_{rf} values corresponding to four oscillations of $V_T(V_{rf})$. It can be seen from this figure that as V_{rf} increases to a value at which the condition

$$V_0 < V_T(V_{rf}) \tag{2}$$

the phase of the charge density wave is localized in hatched region I, which corresponds to oscillations of the charge density wave in one potential well [shown at the right side of this figure is the periodic impurity potential $V_{in}(\theta)$ according to the model of Ref. 3]. At

$$V_0 > V_T(V_{rf}) \tag{3}$$

the phase begins to increase without bound; this behavior corresponds to the motion of a charge density wave. Under condition (2), the phase of the charge density wave is again localized (hatched region II) on the first oscillation of $V_T(V_{rf})$, but now it is localized in two adjacent potential wells (etc.). The physical meaning of the oscillatory dependence $V_T(V_{rf})$ in the model of Ref. 3, and apparently in any model which deals with a periodic impurity potential, is that as V_{rf} is increased, the phase of the charge density wave becomes localized successively in one, two, etc., periodic potential wells over the period of V_{rf}.

Another possibility is that the fine structure on the $\sigma_d(V)$ dependence at $V < V_T$ in the region corresponding to the first oscillation of $V_T(V_{rf})$ stems from the fact that it carries information on the oscillations of the charge density wave in two adjacent potential wells, but this question requires further study.

In summary, the experimental observation of an oscillatory dependence $V_T(V_{rf})$ is one piece of direct evidence for the existence of a periodic potential for the interaction of a charge density wave with impurities in $NbSe_3$.

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[1)] These results were reported in part at the Second All-Union Symposium on Inhomogeneous Electron States.[6] In addition, Thorne *et al.*[7] have recently reported that new data on the nature of the $E_T(E_{rf})$ dependence in $NbSe_3$ will be published in the near future.

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